

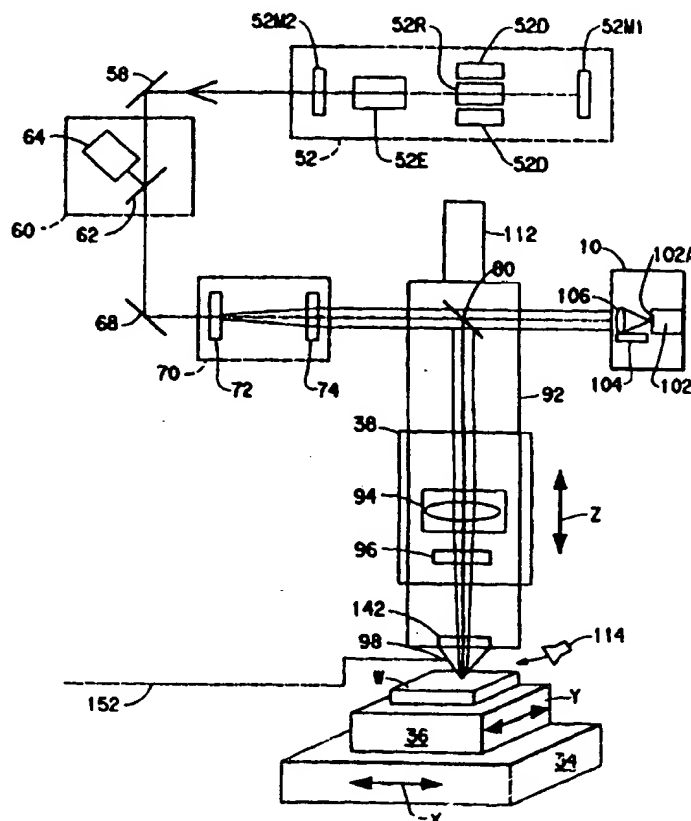


INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶: B23K 26/00, 26/08, 26/14	A1	(11) International Publication Number: WO 97/15417 (43) International Publication Date: 1 May 1997 (01.05.97)
(21) International Application Number: PCT/US96/17226 (22) International Filing Date: 25 October 1996 (25.10.96) (30) Priority Data: 9511695.8 27 October 1995 (27.10.95) EP (34) Countries for which the regional or international application was filed: DE et al. (71) Applicant (for all designated States except US): E.I. DU PONT DE NEMOURS AND COMPANY [US/US]; 1007 Market Street, Wilmington, DE 19898 (US). (72) Inventor; and (75) Inventor/Applicant (for US only): KOBZA, Henry [US/US]; 111 Greenspring Road, Wilmington, DE 19807-2201 (US). (74) Agent: HAMBY, Jane, O.; E.I. du Pont de Nemours and Company, Legal/Patent Records Center, 1007 Market Street, Wilmington, DE 19898 (US).		(81) Designated States: CA, JP, KR, MX, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published <i>With international search report.</i>

(54) Title: METHOD AND APPARATUS FOR LASER CUTTING MATERIALS**(57) Abstract**

An improved method and apparatus of cutting an object with a laser beam, comprising using a diode laser-pumped pulsed solid state laser having an average power output from about 2 to about 100 watts and delivering an average laser beam brightness of greater than 10^{12} W/m²*sr and a peak brightness of greater than 10^{13} W/m²*sr to the object. Objects cut with the laser cutting method having heat affected zones (HAZ) of less than 4 mm, and having substantially no microcracks.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgyzstan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic of Korea	SD	Sudan
CF	Central African Republic	KR	Republic of Korea	SE	Sweden
CG	Congo	KZ	Kazakhstan	SG	Singapore
CH	Switzerland	LI	Liechtenstein	SI	Slovenia
CI	Côte d'Ivoire	LK	Sri Lanka	SK	Slovakia
CM	Cameroon	LR	Liberia	SN	Senegal
CN	China	LT	Lithuania	SZ	Swaziland
CS	Czechoslovakia	LU	Luxembourg	TD	Chad
CZ	Czech Republic	LV	Latvia	TG	Togo
DE	Germany	MC	Monaco	TJ	Tajikistan
DK	Denmark	MD	Republic of Moldova	TT	Trinidad and Tobago
EE	Estonia	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	UG	Uganda
FI	Finland	MN	Mongolia	US	United States of America
FR	France	MR	Mauritania	UZ	Uzbekistan
GA	Gabon			VN	Viet Nam

TITLE

METHOD AND APPARATUS FOR LASER CUTTING MATERIALS

BACKGROUND OF THE INVENTION1. Field of the Invention

5 The present invention relates to a method for laser cutting a manufactured object by means of a focused high energy laser beam, a system for precision processing and machining of materials, and manufactured objects having been cut by this method.

10 2. Description of the Related Art

The method of cutting manufactured objects by means of a focused laser beam is in general known in the art. Most commercial systems use a fiber optic bundle to deliver the beam to the cutting station. However, the
15 use of fiber optics is totally unsuitable for precision cutting since the fiber optics very badly degrade the beam quality. A beam quality factor M^2 (as defined below) for a fiber delivered beam is typically in the 50 to 150 range whereas a beam quality factor M^2 of less
20 than 2 is needed for precision cutting. Since M^2 enters the equation for brightness (as defined below) as its square in the denominator, fiber coupled lasers fail the necessary brightness by orders of magnitude.

Only a few references discuss using a laser beam
25 directly for cutting. Typical is Johnson et al., US patent 5,057,664, which describes the use of a diode pumped, Q-switched YAG laser for cutting very thin (about 1 mm or less) films of materials having a high melting point, such as nichrome or tantalum nitride, as used for
30 thin-film resistors. They report a trim profile with a good smoothness.

Basu et al., US patent 4,890,289, describe a high energy diode pumped solid state laser arrangement applicable, e.g., for laser cutting. To avoid distortion
35 of the laser gain material by heat generated together with the radiation, they propose to arrange the pumping diodes in a certain distance from the laser material, to guide and concentrate the pumping radiation by means of

fiber optics, and to cyclically move the pumped region to distribute the heat generated in the laser by the optical pumping radiation. Such an arrangement needs obviously rather sophisticated mechanical and control means.

- 5 Further, a slab laser, such as disclosed in Basu et al. is less preferred than a rod laser for precision cutting since a slab laser typically exhibits astigmatism which also prevents the beam quality factor M^2 from being in the desired range.

- 10 Baer, US patent 5,059,764, employs an end-pumped, fiber coupled, solid state rod laser pumped by laser diodes, for application to semiconductor manufacture and repair. The beam width in this device can be as low as 1 - 2 mm, and the pulses have typically an energy of 30 mJ.
- 15 Single pulses are employed to ablate undesired links in semiconductor circuits.

- The methods of Johnson et al. and Baer described above are useful for shaping of rather thin objects like metal layers in semiconductor circuits and the material
- 20 is removed mainly by ablation. The method of Basu et al. is generally suitable for thicker materials but can only make relatively coarse cuts, i.e., about ten times wider than desirable. There remains a need for a method to make precision microcuts in thicker manufactured objects,
- 25 i. e., of cuts having a high aspect ratio L/D between material thickness L and cut width D . Kobsa et al., US patent 5,168,143, have employed a laser beam to cut complex capillaries in spinneret plates. Such plates are typically of metal and are 0.2 to 1.0 mm thick, although
- 30 they can be as thin as 0.1 mm or as thick as 2.0 mm. In this process the focused laser energy creates a pool of molten material between the face (upper) and the bottom (lower) surface of the plate and the molten metal is expelled by means of a pressurized fluid flowing
- 35 coaxially with the laser beam. The laser beam is substantially a single-mode beam and is focused to a spot size of less than 100 μ m on a location above the upper surface of the plate. The laser is preferably pumped

with xenon flash tubes and operated at a repetition frequency between 100 and 200 Hz. By this method, cuts about 40 mm wide and with satisfactory smooth edges could be made in metal and ceramic plates of some 0.2 to 1.3 mm thickness.

Specific to this method is the occurrence of a heat affected zone (HAZ) at the surface of the kerf. This may be caused by molten material which was not removed by the fluid jet but solidified due to heat dissipation in the manufactured object by recrystallization, or by the occurrence of cracks due to thermal stress or by other effects. The thickness of the HAZ created by known methods of laser cutting depends on material being cut and by process parameters and is typically 25 to 50 mm. Generally the material in the HAZ has different physical and chemical properties than the bulk material. Thus it may happen that when the manufactured object is in use the heat affected zone is less resistant to mechanical wear and/or to chemical attack than the bulk material and the dimension of the cut region may change rapidly when in use. This is obviously a disadvantage.

Therefore it is the object of the present invention to improve the laser cutting process in such manner that the thickness of the heat affected zone in a laser cut object is significantly less than that achieved by the prior art.

SUMMARY OF THE INVENTION

According to the invention there is provided a method for cutting through a manufactured object with a thickness of about 0.1 to 2.0 mm that includes the steps of using a laser having side-pumped diode bars, which has an average power output from about 2 to about 100 watts and delivers an average laser beam brightness of greater than 10^{12} W/m²*sr and a peak brightness of more than 10^{13} W/m²*sr to produce a laser beam. The laser beam is focused to a plane between the upper and the lower surface of the object, which either melts or vaporizes the material. The melted or vaporized material is

expelled by the laser beam from the object by a pressurized fluid flowing coaxially with the laser beam.

The invention also comprises a laser based system for precision processing and machining of materials and workpieces. This system comprises a solid state laser light source comprising a laser medium, preferably a cylindrical rod of neodymium-doped yttrium aluminum garnet (Nd:YAG), a laser cavity defined by two end mirrors, a multiplicity of diode bars arranged around the laser medium for pumping it, and optical elements for improving the beam quality. Such optical elements are generally known and may be apertures for selecting single modes (e. g. the TEM₀₀ mode), lenses, or curved mirrors. The system further comprises a lens system for expanding, collimating, and focusing the laser beam. The focusing lens may be located close to the collimator or at some distance to leave space for other parts of the system, like beam attenuators or beam splitters for beam diagnostic. The system further comprises a workstation for holding and moving a workpiece with respect to the laser beam. This workstation holds the workpiece, e. g., by clamping elements, and has means to independently move the workpiece in two orthogonal directions and to independently move the focus point of the laser in a third direction, orthogonal to the first two directions.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1 is a pictorial view showing the apparatus of the present invention.

Fig. 2 is a stylized diagrammatic view of the optical elements of the invention.

Fig. 3 is a elevational view, partly in section, showing the laser beam delivery assembly.

Fig. 4 is a perspective view of the laser rod and pumping diodes, showing a preferred arrangement for optically pumping the laser rod.

DETAILED DESCRIPTION OF THE INVENTION

The average brightness of a laser B_{av} depends on the laser power, and on the cross section as well as on the solid angle of the laser beam in its focal plane. It is here defined for a pulsed laser by the following formula:

$$B_{av} = (n * E) / (A * Q) \text{ [W/m}^2\text{*sr]}, \text{ where}$$

E [J] = energy per pulse,

n [1/s] = repetition rate,

A [m²] = cross section of the beam in the focal plane,

Q [sr] = solid angle encircled by the beam at the waist

Q [sr] = solid angle encircled by the beam at the waist

For a CW laser, $n * E$ has to be replaced by the power in [W].

In units which can be measured easier this becomes

$$B_{av} = (4/\pi)^2 * (n * E) / (W_0^2 * q^2) \text{ [W/m}^2\text{*sr]},$$

where

W_0 [m] = diameter of the beam at the waist,

q [rad] = divergence of the laser beam.

The divergence q can be determined as the ratio between the diameter of the collimated beam before entering the focusing lens and the focal length of this lens.

Since W_0 is more conveniently measured in mm, this becomes

$$B_{av} = 10^{12} * (4/\pi)^2 * (n * E) / (W_0^2 * q^2) \text{ [W/m}^2\text{*sr]}.$$

The peak brightness is obtained when dividing B_{av} by the duty cycle r :

$$B_p = B_{av} / r \text{ [W/m}^2\text{*sr]}.$$

The duty cycle means e. g. for equal and essentially rectangular laser pulses the ratio of the duration of a laser pulse to the time interval between start of one pulse and start of the next.

It follows that in order to obtain a high brightness one has either to increase the pulse energy E or to decrease the product W_0*q which describes the beam quality, or both. The minimum value for W_0*q is equal to the diffraction limit $4 \lambda/p$, where λ is the wavelength of the laser radiation. For further discussion a beam quality factor M^2 is used, which is the ratio between the actual and the minimum value of (W_0*q) and is defined in the equation:

$$W_0*q = M^2 * 4 * \lambda / p. \text{ [m*rad]}$$

Using this we get for the average brightness

$$B_{av} = (n*E) / (\lambda^2*(M^2)^2) = 0.883*10^{12}*n*E / (M^2)^2 \text{ [W/m}^2\text{*sr]}$$

for the Nd:YAG laser with $\lambda = 1.064 \text{ mm}$.

This means that in order to obtain high brightness for a laser, the beam quality factor M^2 must be as low as possible. The apparatus of the present invention controls M^2 by: (1) correcting thermal lensing by either using one or more lenses inside the laser cavity or using one or two curved end mirrors; and (2) minimizing thermal loading of the laser medium to avoid higher order distortions such as astigmatism, which are difficult or impossible to correct, as will be explained below.

The apparatus of the present invention is shown generally at 10. Apparatus 10 comprises a vibration-free support structure 20, a three-axis positioning system 30, a workpiece holding fixture 40, a laser system 50, a laser beam attenuator 60, a laser beam expander 70, a

beam sampler 80, a laser beam delivery assembly 90, a laser beam quality monitor 100, a cutting zone viewing system 110, a capacitive distance sensor 140, a pressurized-gas cutting assist unit 150, and a light-tight safety enclosure 160.

The laser cutting system 50 is based on a laser diode-pumped pulsed Nd:YAG solid state laser head 52. A laser system 50 includes a laser cavity defined by two end mirrors, a laser medium, a multiplicity of diode bars for pumping the laser medium, and at least one optical element for improving the beam quality. A laser system manufactured by Fibertek, Inc. of Herndon, VA as model 3621-3000-1 comprises a laser head 52, power supply 54 and thermal cooling unit 56. The laser medium, comprising a laser rod 52R in the laser head, is pumped by eighty (80) laser diode bars of 50 W each. These diode bars are arranged in five arrays, 52D1 through 52D5, of 4 by 4 alongside the perimeter of the laser rod. Figure 4 illustrates this arrangement. The average laser power may be from about 2 watts to about 100 watts, preferably about 30 watts. The pulse length is 150 micro seconds [ms] and the pulse repetition rate is 1000 pulses per second [1/s] which corresponds to a duty cycle of 0.15. The diodes 52D and the laser rod 52R are chilled by a water-to-air cooling unit 56.

It is important that the temperature distribution in the laser medium be as symmetrical as possible. This is often easier to accomplish in a cylindrical rod shaped laser medium, because of its symmetry, than in a slab shaped laser medium. In the most preferred embodiment of the invention, as seen in Fig. 5, a rod laser medium is side-pumped by a number (such as five) of arrays of laser diode bars, to achieve a uniform temperature distribution which will vary radially but varies as little as possible circumferentially. The cylindrical rod 52R is preferably enclosed in a transparent quartz tube 52Q through which a temperature controlled coolant, such as deionized water supplied by a cooling unit 56, flows at a constant rate

to maintain the laser rod 52R at a constant average temperature. The bars that hold the pumping laser diodes 52D are made of a heat sink material having a high thermal conductivity through which the temperature
5 controlled coolant from the cooling unit 56 flows at a constant rate to maintain the pumping laser diodes at a constant average temperature. To get a high pulse energy, it is preferred in the method according to the invention to use a side-pumped laser rod 52R with the
10 pumping laser diodes 52D directly coupled to the laser rod 52R for maximum optical pumping efficiency.

Particularly preferred is a cylindrical rod shaped laser medium. An array of pumping diodes is arranged close to the laser medium. The pumping diodes are
15 preferably disposed around the perimeter of the laser medium. This way a greater number of diodes, e.g., 20 to 160, can be arranged close to the laser medium, each having an output pumping radiation power of 20 watts to 100 watts so that a pumping power of several kilowatts
20 can be achieved. At the same time the pumping energy is more uniformly distributed over the laser medium and thermal stress is lower. For best thermal uniformity within the laser rod an arrangement having an odd number, such as five or seven, of diode bar array lines
25 symmetrically arranged around the laser rod is preferred. An odd number is preferred so that optical energy from one diode bar array line that is not absorbed by the laser rod does not impinge upon an opposite diode bar array line. With the present invention, a beam quality
30 factor of $M^2 = 1.2$ is obtained by using one or more curved end mirror and by side-pumping the laser medium.

The beam attenuator 60 may be, e. g., a grey (neutral density) filter of varying density, also known as a wedge filter, or a partially reflective mirror
35 (partially reflective beam splitter) of varying reflectivity 62, as shown in figure 2, which can be moved in a direction essentially perpendicular to the optical path. Reflected laser energy is absorbed by beam dump

64. Particularly preferred as the attenuator 60 is a diffractive laser beam attenuator, also known as a diffractive beam splitter. It is also advantageous if the beam splitter is continuously variable over a wide
5 attenuation range so that the beam power may be selected over this range to accommodate the material being cut. A suitable attenuator is an Optical Power Modulator model OPM 121-45021 sold by Gentec Inc., Saint-Foy, Quebec, Canada.

10 The beam attenuator can conveniently be located at any place between the outcoupling mirror 52M2 of the laser head 52 and the final focusing lens 94. For example, it can be located immediately after the corner mirror 58 as illustrated in Figures 1 and 2 or be
15 inserted into the lens system after the beam has been expanded and collimated.

The beam passes through a beam attenuator 60 as described above. Then it goes through a beam expanding lens 72 which, dependent on the application, expands the
20 beam to a diameter of 5 to 20 mm and a beam collimating lens 74 which collimates the beam. Next a beam sampler 80, comprising a beam splitter mirror, separates about 0.1 % of the beam to the laser beam quality monitor 100 for beam diagnosis and reflects 99.9 % of the beam to the
25 laser beam delivery assembly 90 which focuses the beam at the cutting station. The beam sampler 80 is transparent to visible light to allow monitoring of the cutting process as described in conjunction with cutting zone viewing system 110. The portion of the beam detected by
30 the CCD camera 102 of the laser beam quality monitor 100 generates an on-line picture of the laser beam contour which is displayed on a monitor 109 for visually monitoring beam quality by the operator. The focusing lens 94 of the laser beam delivery assembly 90 has a
35 focal length of eighty millimeters (80 mm). The nozzle 98, which is mounted on laser beam delivery assembly 90, directs a jet of a fluid coaxial with the laser beam at the surface of the workpiece, similar to Kobsa, US patent

5,168,143. Preferred fluids in the pressurized-gas cutting assist unit 150 for cutting are oxygen, nitrogen, carbon dioxide, and argon, the pressure of which can be controlled to achieve optimum cutting quality and can, for example be about 0.5 MPa. The support structure 20 is preferably made of granite rock, or similar material, such as a unit available from Thyssen Laser-Technik GmbH, to reduce vibration and to maintain proper alignment of the optics.

10 The three-axis positioning system 30 comprises a controller 32, an X-axis positioning stage 34, a Y-axis positioning stage 36, and a Z-axis positioning stage 38. Each positioning stage 34, 36, 38 has a respective moveable table 34T, 36T, 38T. The laser system 50
15 comprises a laser head 52, a laser power supply 54 and a laser cooling unit 56. The laser beam expander 70 comprises a beam expanding lens 72 and beam collimating lens 74. The laser beam delivery assembly 90 comprises a beam delivery tube 92, an objective or focusing lens 94,
20 a window 96, and a nozzle 98.

The laser beam quality monitor 100 comprises a beam imaging CCD camera assembly 102 having a focus control unit 104 and an image processor/control unit 108. The small portion of the laser beam energy passing through
25 beam sampler 80 passes through the focus control unit 104 and is focused onto a planar CCD array 102A of the beam imaging CCD camera assembly 102. The image processor/control unit 108 controls the focus control unit 104 to position a focusing lens 106 at several
30 specific positions. A first position of lens 106 corresponds to focusing the beam exactly onto the CCD array 102A, a second position of lens 106 corresponds to focusing the beam at a position a small distance from the plane of CCD array 102A, a third position of lens 106
35 corresponds to focusing the beam at a position a larger distance from the plane of CCD array 102A. The images generated at these varying focal positions are received by the image processor/control unit 108, which in turn

calculates the beam quality factor M^2 . in accordance with the method published in Chapters 3 and 4 of Herziger and Loosen, Werkstoffbearbeitung mit Laserstrahlung, Carl Hanser Verlag, Munchen, 1993.

5 The cutting zone viewing system 110 comprises a CCD camera assembly 112, an auxiliary light source 114, and an image display unit 116. The cutting zone viewing system 110 is mounted on the Z-axis positioning stage 38 adjacent to the laser beam delivery assembly 90. Light
10 reflecting from the cutting zone on the workpiece, either from the laser beam or from the auxiliary light source 114, is collimated by the objective lens 94 and passes through beam sampler 80. A lens 112L in camera assembly 112 focuses an image of the cutting zone onto a CCD
15 imaging array 112A in the camera 112.

 The support structure 20 comprises a base 22, upon which are mounted two support columns 24 upon which is mounted an upper platform 26. The workpiece holding fixture 40 is mounted on the Y-axis positioning stage 36,
20 which is in turn mounted on the X-axis positioning stage 34, which in turn is mounted on base 22 of support structure 20. The laser head 52, the corner mirror 58, the laser beam attenuator 60, the corner mirror 68, the laser beam expander 70, and the Z-axis positioning stage
25 38 are mounted on upper platform 26. The laser beam delivery assembly 90 is mounted on the Z-axis positioning stage 38.

 Suitable for use as the three axis positioning subsystem 30 is a commercial unit available from
30 Aerotech, Inc. of Pittsburgh, PA comprising a model UNIDEX(R) model 31 series controller 32, a model ATS 50060 positioning stage which serves a X-axis stage 34, a model ATS 50060 positioning stage which serves as Y-axis stage 36, and a model ATS 50060 positioning stage which
35 serves a Z-axis stage 38.

 The capacitive distance sensor 140 comprises a distance sensing element 142 and a control module 144. The output of module 144 is connected via a cable 146 to

controller 32. Distance sensor 140 measures the distance
from the objective focusing lens 116 to the surface of
the workpiece. Sensing element 142 may be mounted on
nozzle 98. In operation the control module 144 sends an
5 electrical signal representative of the objective lens to
workpiece distance and the controller 32 sends a control
signal to the Z-axis stage
38 to position the stage table 38T and thus the laser
beam delivery assembly 90 to maintain the desired
10 distance from the surface of the workpiece and thus to
cause objective lens 94 to focus the laser beam at the
desired position with respect to the surface of the
workpiece.

A gas cutting assist unit 150, comprising a source
15 150C of gas, a supply tube 152 and a cutting nozzle 98,
mounted in coaxial alignment with the laser beam between
the focusing lens 94 and the workpiece W, directs a jet
of a pressurized fluid to the surface of the workpiece
held in the workstation. This fluid is preferably a gas
20 like oxygen, argon, carbon dioxide, or nitrogen.

Further in accordance with the present invention,
there is provided a method for cutting an object with a
thickness of about 0.1 to 2.0 mm. The method includes
the steps of using a laser having side-pumped diode bars,
25 which has an average power output from about 2 to about
100 watts and delivers an average laser beam brightness
of greater than 10^{12} W/m²*sr and a peak brightness of
more than 10^{13} W/m²*sr to produce a laser beam. The
laser beam is focused to a plane between the upper and
30 the lower surface of the object, which either melts or
vaporizes the material. The melted or vaporized material
is expelled by the laser beam from the object by a
pressurized fluid flowing coaxially with the laser beam.

35 Pulsed lasers are preferred in the method according
to the invention because they permit achieving a very
high peak brightness without excessive thermal load on
the system. It is further preferred to operate the laser

cutting equipment with a repetition frequency n of at least 500 pulses per second [1/s].

Further preferred in the method according to the invention is to operate the laser 50 at a constant average power output so that optimum beam quality may be maintained and to modulate the intensity of the laser beam by an attenuator 60 which is arranged in the optical path between the laser head 52 and the workpiece W, preferably immediately after the laser head 52. Thus the laser runs at a constant average power level and the effective average power of the laser beam at the workpiece is adjusted by the attenuator 60 to the level desired for the specific application. It is generally advantageous to adjust the power of the laser beam at the workpiece to a level just sufficient to achieve laser cutting. The use of an excessive power level increases the heat affected zone. This means that the unavoidable thermal lensing in the laser medium which is caused by the radial non-uniformity of refractive index within the medium, which again is caused by the radial temperature gradient, can be held constant and can be effectively corrected by an appropriate design of the resonator cavity, or by the use of an optical correcting element 52E as is illustrated in Figure 2.

Further preferred is to monitor the distance between the focusing lens 94 and the surface of the workpiece W and to control this distance to a constant value. Thus the influence of unevenness or bends in the workpiece can be eliminated and the laser beam focal point can be maintained at the desired position relative to the surface of the workpiece. Such control is preferably achieved by a distance sensor system 140, such as a Lasermatic® II, available from Precitec GmbH of Gaggenau, Germany, which has a capacitive sensor 142 mounted on the laser beam delivery tube 92, which provides an electrical signal to the control unit 32 of a suitable three-coordinate workstation 30, which in turn maintains the

laser beam focal point at the desired position relative to the surface of the workpiece.

When cutting thick objects it must be kept in mind that the minimum cross section area of the beam and therefore the highest fluence or brightness is limited to just one plane. Over and under this plane the beam is wider as a consequence of the focusing optics. This is described by the so called Rayleigh length Z_R which is the distance over which the beam diverges to twice its minimum area (at the waist) and is given by

$$Z_R = W_0^2 * \pi / (M^2 * \lambda) = 4 W_0 / q ,$$

where Z_R , W_0 , and λ are measured in the same units.

Typically, material up to about two Z_R thick or slightly thicker can be cut with good quality. That means that Z_R is preferably greater than 0.4 times the material thickness.

The Rayleigh length Z_R can be controlled by selecting the appropriate beam expander. Expanding the beam more gives a smaller beam waist W_0 , i. e., a smaller divergence q but also a smaller Rayleigh length Z_R . On the other hand, the smaller the beam diameter at the waist W_0 is, the narrower can be the cutting kerf. When cutting material about two Z_R thick, the achievable kerf width is about 1.4 times W_0 . In practice, the achievable kerf width is slightly larger than this value, depending upon the thermal conductivity of the material being cut.

The cutting method according to the invention can be applied to a variety of materials. Preferred are metals like stainless steel, copper, aluminum, even high melting point metals like tungsten, and ceramic materials like alumina (e. g. KERAMTEC® 708 of Hoechst), silicon carbide, or zirconia. Also composite materials like carbon fiber reinforced thermosetting resins, carbon fiber reinforced

carbon, or clad materials like stainless steel coated with a ceramic layer can be cut.

It was found that the cutting surfaces obtained by the method of the present invention were very smooth and had a very thin HAZ, typically not thicker than 4 mm. This is due to the very low value of M^2 for the laser cutting equipment according to the invention and to adjusting the effective power per pulse to a level which is just adequate for cutting but does not deposit excess energy on the workpiece. When cutting brittle materials like ceramics it was found that, contrary to the results with prior art methods, there were substantially no microcracks present in the cut surface.

The method of the present invention can be applied in different technical fields, e. g., for precision cutting of metal sheets in the automobile industry, in the manufacturing of precision ceramic parts for the electrical and electronics industry, of spinneret plates for the fibers industry, and of fuel injection nozzles, such as for diesel engines.

An optical path is defined in the system which extends from the laser head to the workpiece. Optical elements like mirrors, lenses, or beam splitters can be present in the optical path as usual in the art.

It was found that this laser system could be arranged in a relatively small enclosure because of the compact structure of the diode side-pumped laser and the moderate power consumed. Therefore it is preferred to enclose the system in an outer housing, the doors of which are interlocked with the laser power supply. This setup can then be treated as a Class I laser system in accordance with recognized laser safety standards.

Example 1

A 0.5 mm thick sheet of stainless steel was cut with the device described above at a cutting speed of 3 m/min and at the full average laser power of $n \cdot E = 30$ watts. The beam quality M^2 as defined above was found to be 1.2.

The peak brightness in this experiment calculated as described above was $B_p = 12.3 \cdot 10^{13} \text{ [W/m}^2\text{*sr]}$ and the average brightness was $B_{av} = 18.4 \cdot 10^{12} \text{ [W/m}^2\text{*sr}]$.

5

Example 2

In a second experiment, a stainless steel sheet 0.2 mm thick was cut at a rate of 0.2 m/min. By visually observing the cutting process on monitor 116 and setting the attenuator 60 to the power just sufficient for cutting, the average laser power applied was $n \cdot E = 2.5$ watts. The beam quality was unchanged from that of Example 1, i.e., the beam quality factor M^2 was equal to 1.2. The brightness applied in this experiment was $B_p = 1.03 \cdot 10^{13} \text{ [W/m}^2\text{*sr]}$ and $B_{av} = 1.53 \cdot 10^{12} \text{ [W/m}^2\text{*sr}]$.

15

The width of the HAZ was measured by a metallographic technique (polishing and etching) and was found to be 2 mm for the material cut in both Examples 1 and 2. In further tests it was found that the beam quality factor was also maintained at intermediate cutting speed and at an average laser power such as 10 watts.

20

In comparison to these results, the prior art method described by Kobsa, US patent 5,168,143, with $n \cdot E = 11 \text{ W}$, $W_0 = 42 \text{ mm}$, and $q = 80 \text{ mrad}$, which corresponds to an average brightness of $B_{av} = 0.4 \cdot 10^{12} \text{ [W/m}^2\text{*sr}]$, gave a HAZ significantly thicker than 5 mm, i.e., up to about 25 mm.

25

WHAT IS CLAIMED IS:

1. A laser based system for precision processing and machining of materials, comprising

- 5 (a) a pulsed solid state laser, comprising,
(i) a laser cavity defined by two end mirrors,
(ii) a laser medium;
(iii) a cylindrical laser rod directly side-pumped by a plurality of arrays of laser diode, and
10 (iv) at least one optical element for improving the beam quality,
(b) a laser beam delivery system for expanding, collimating, and focusing the laser beam;
(c) a workstation for holding and moving a workpiece with respect to the laser beam;
15 (d) a cutting nozzle for directing a jet of a pressurized fluid to the surface of said workpiece: wherein the laser beam has an average power from about 2 to about 100 watts and the focused laser beam has an average brightness of more than 10^{12} W/m²*sr and a peak
20 brightness of more than 10^{13} W/m²*sr.

2. The system of claim 1, wherein the solid state laser medium is neodymium-doped yttrium aluminum garnet (Nd:YAG).

3. The system of claim 1, further comprising a
25 continuously variable beam splitter external to the laser cavity.

4. The system of claim 1, further comprising a beam sampler in the optical path, and a laser beam quality monitor, said beam sampler directing a minor
30 fraction of the beam to a laser beam quality monitor.

5. The system of claim 4, wherein the laser beam quality monitor comprises a CCD camera assembly having a planar CCD array, a focus control unit and an image processor/control unit wherein the portion of the laser
35 beam energy passing through the beam sampler passes through the focus control unit and is focused onto the planar CCD array to generate an image of the laser beam for monitoring laser beam quality.

6. The system of claim 1, further comprising a distance sensor fixed to the laser beam delivery system, which generates an input to the workstation, which controls the distance between the focusing lens and the surface of the material.

7. A method for cutting a manufactured object with a thickness of about 0.1 to 2.0 mm that includes the steps of (a) using a laser having a cylindrical laser rod directly side-pumped by a plurality of arrays of laser diodes, wherein the laser has an average power output from about 2 to about 100 watts and delivers an average laser beam brightness of greater than 10^{12} W/m²*sr and a peak brightness of more than 10^{13} W/m²*sr to produce a laser beam;

(b) focusing the laser beam to a plane between the upper and the lower surface of the object, to melts or vaporizes the material;

(c) expelling the melted or vaporized material by the laser beam from the object by a pressurized fluid flowing coaxially with the laser beam.

8. The method of claim 7, wherein the laser has an M² beam quality factor of less than 2.

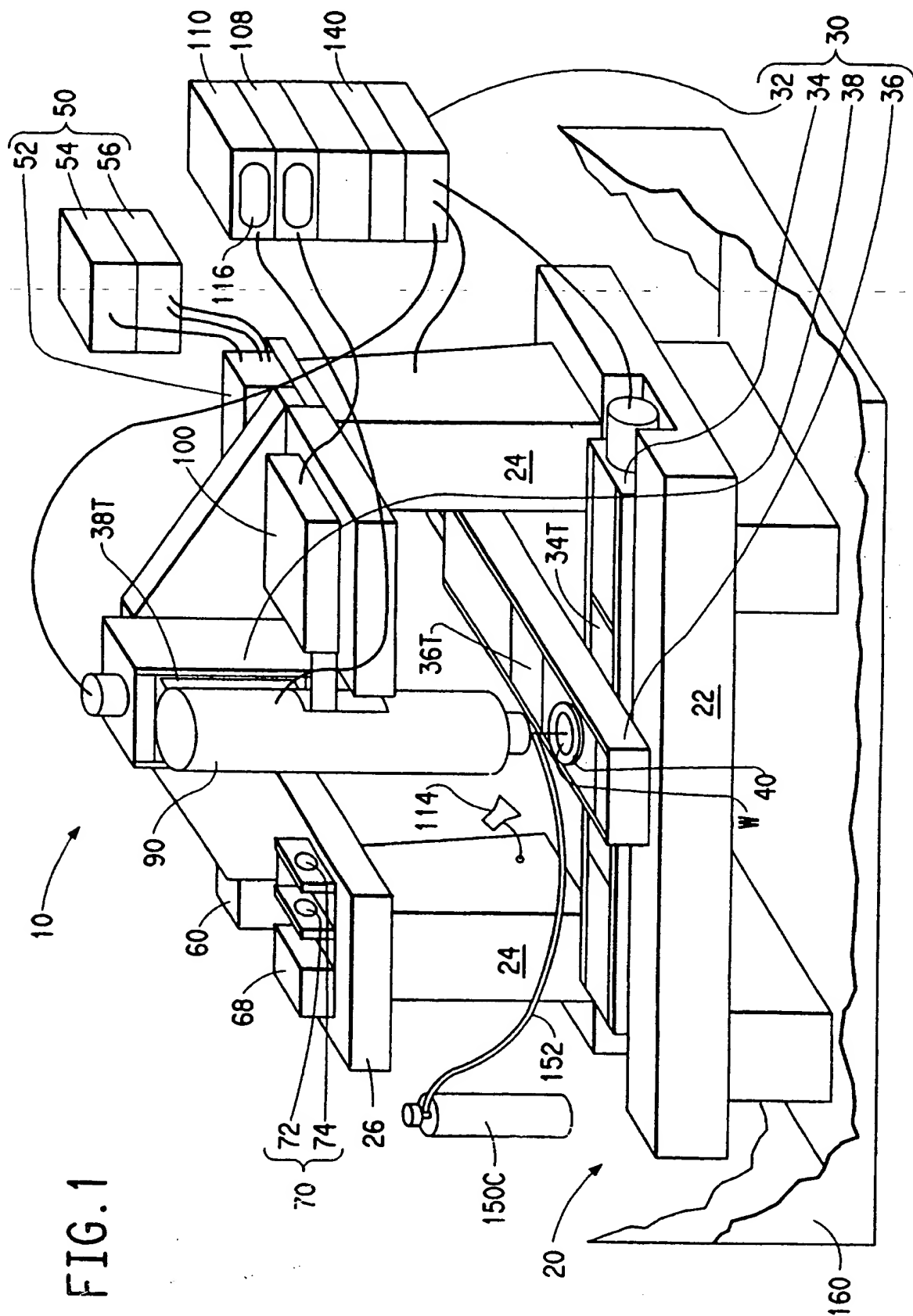
9. The method of claim 7, wherein the laser has an M² beam quality factor of less than 1.5.

10. The method of claim 8, wherein the laser output is held at a constant average power such that the M² beam quality factor of less than 2.0 is maintained and wherein the laser beam intensity is modulated by an attenuator disposed in the optical path between the laser and the object to a level just sufficient to achieve laser cutting of the object, so that the heat affected zone in the object is minimized.

11. The method of claim 7, wherein the distance between the focusing lens of the laser beam and the surface of the material is controlled automatically.

12. The method of claim 7, wherein the Rayleigh length of the laser beam is greater than about 0.4 times the thickness of the material being cut.

1/4



1/4

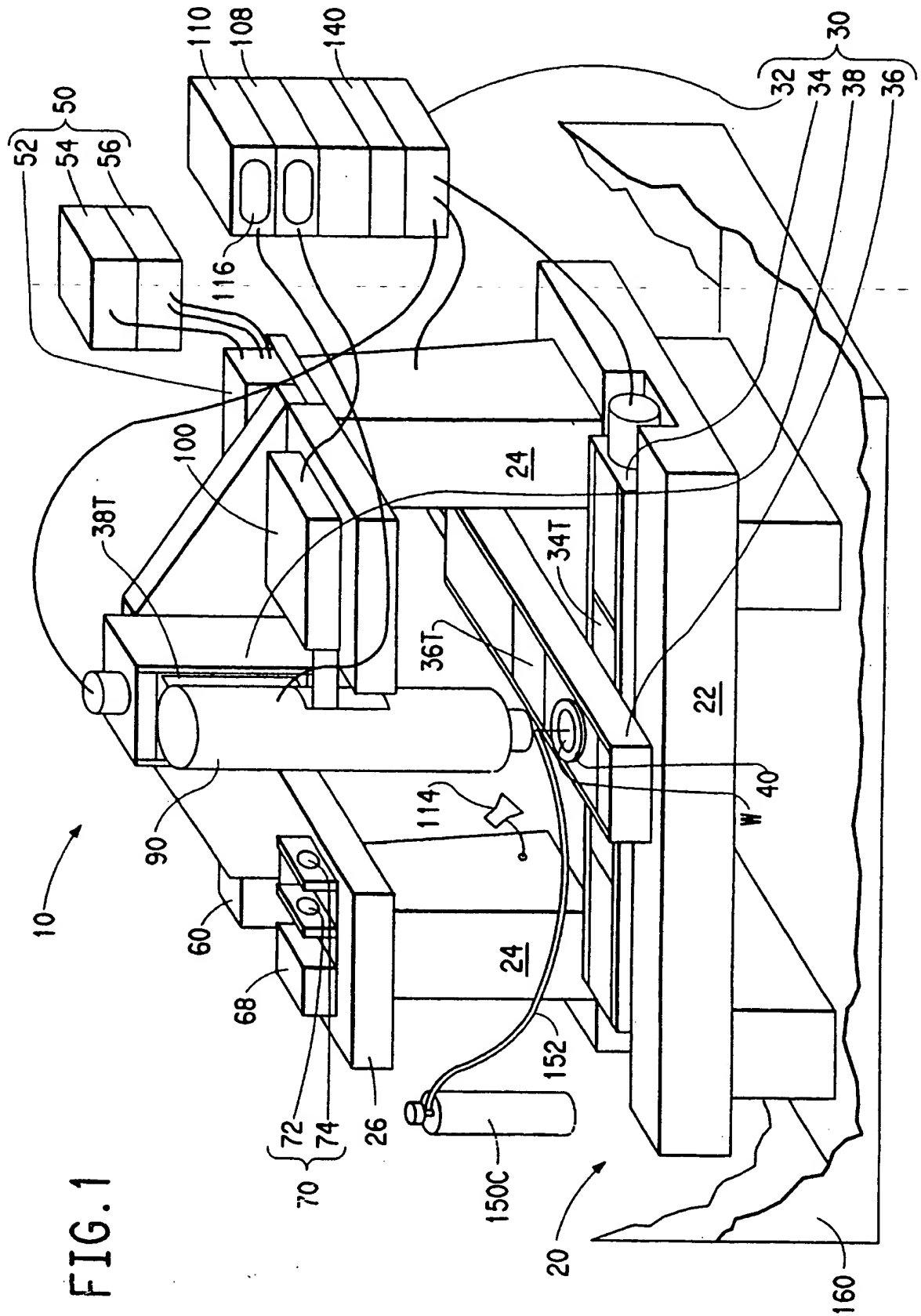


FIG. 1

2/4

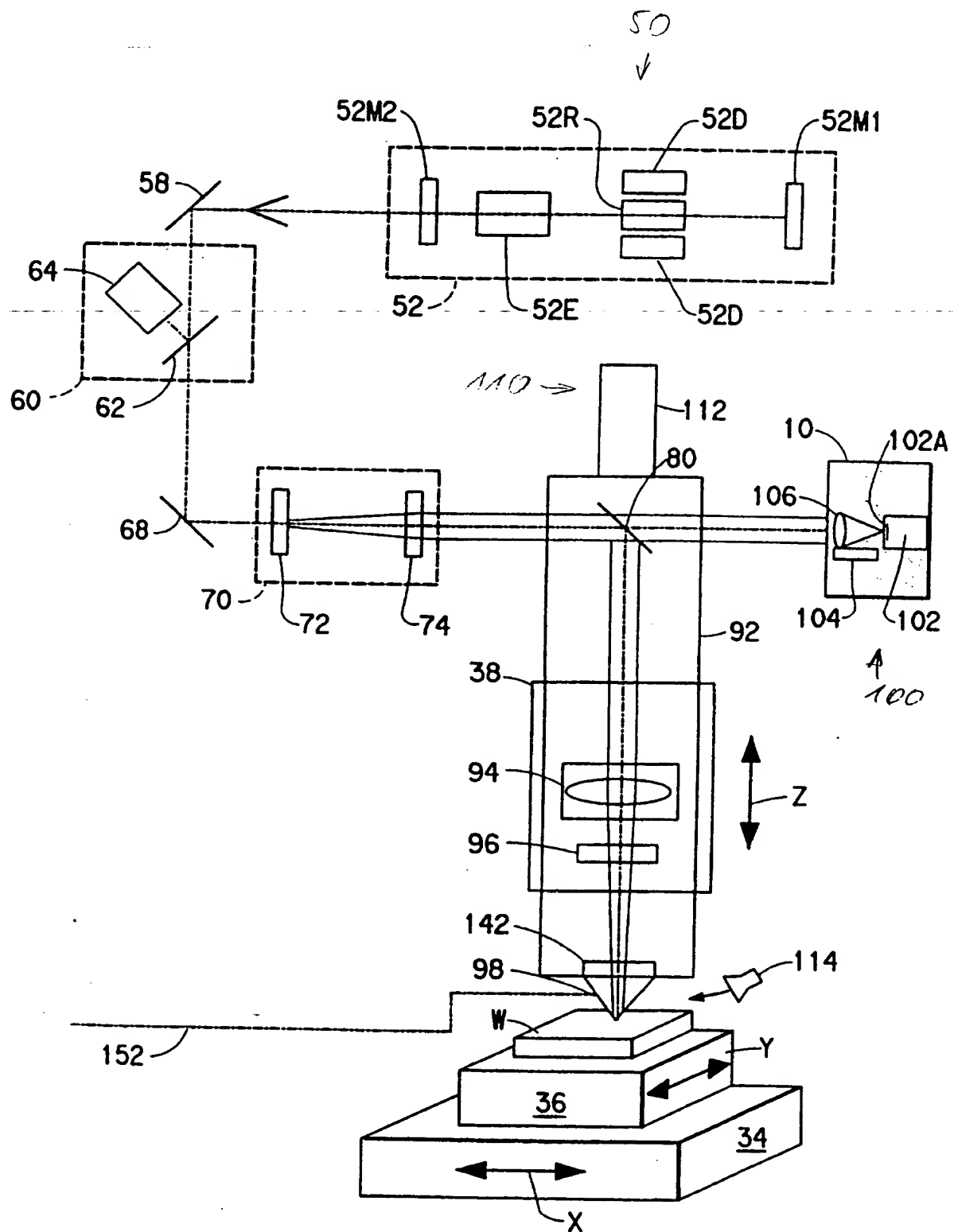


FIG. 2

3/4

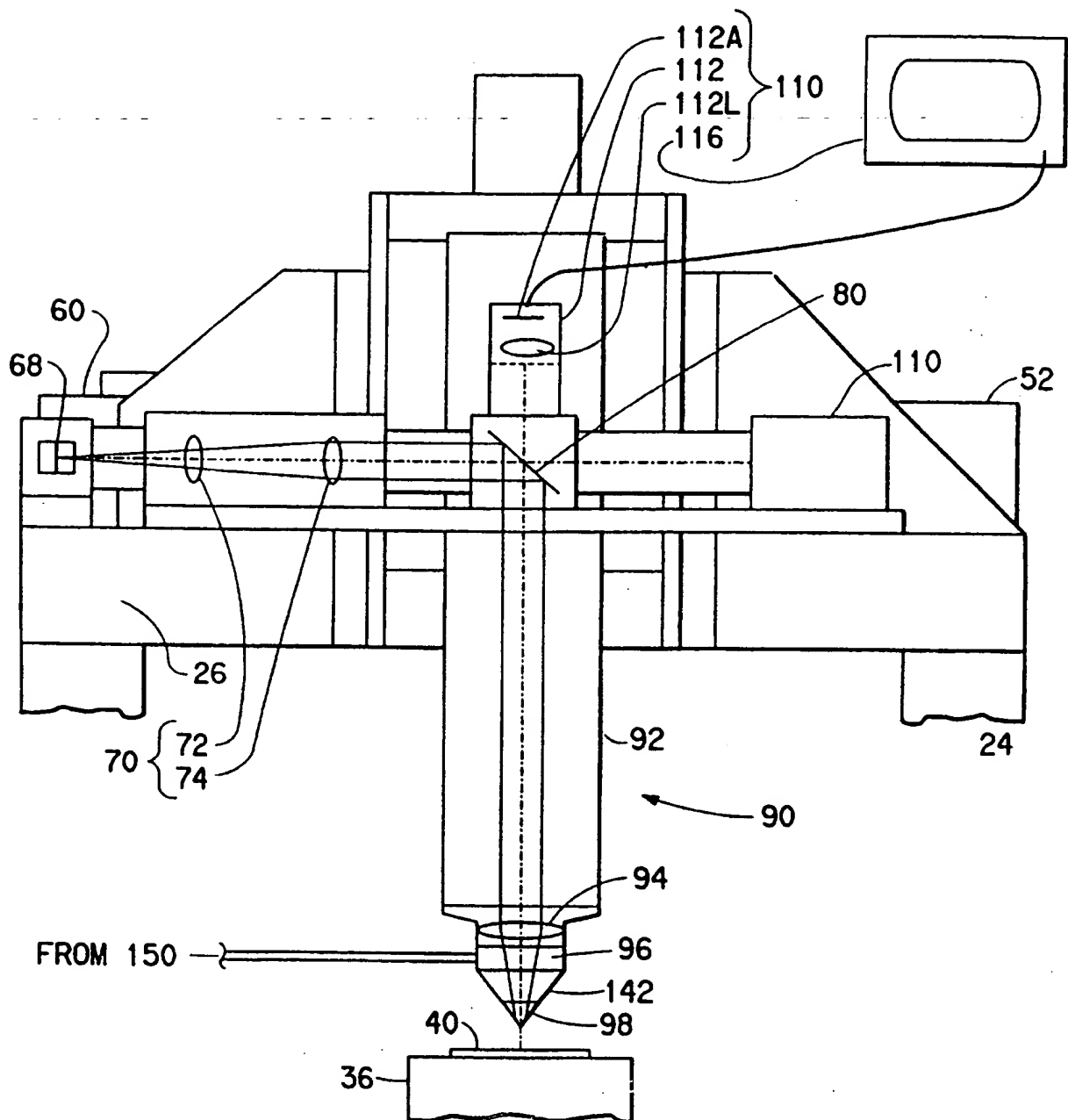


FIG. 3

4/4

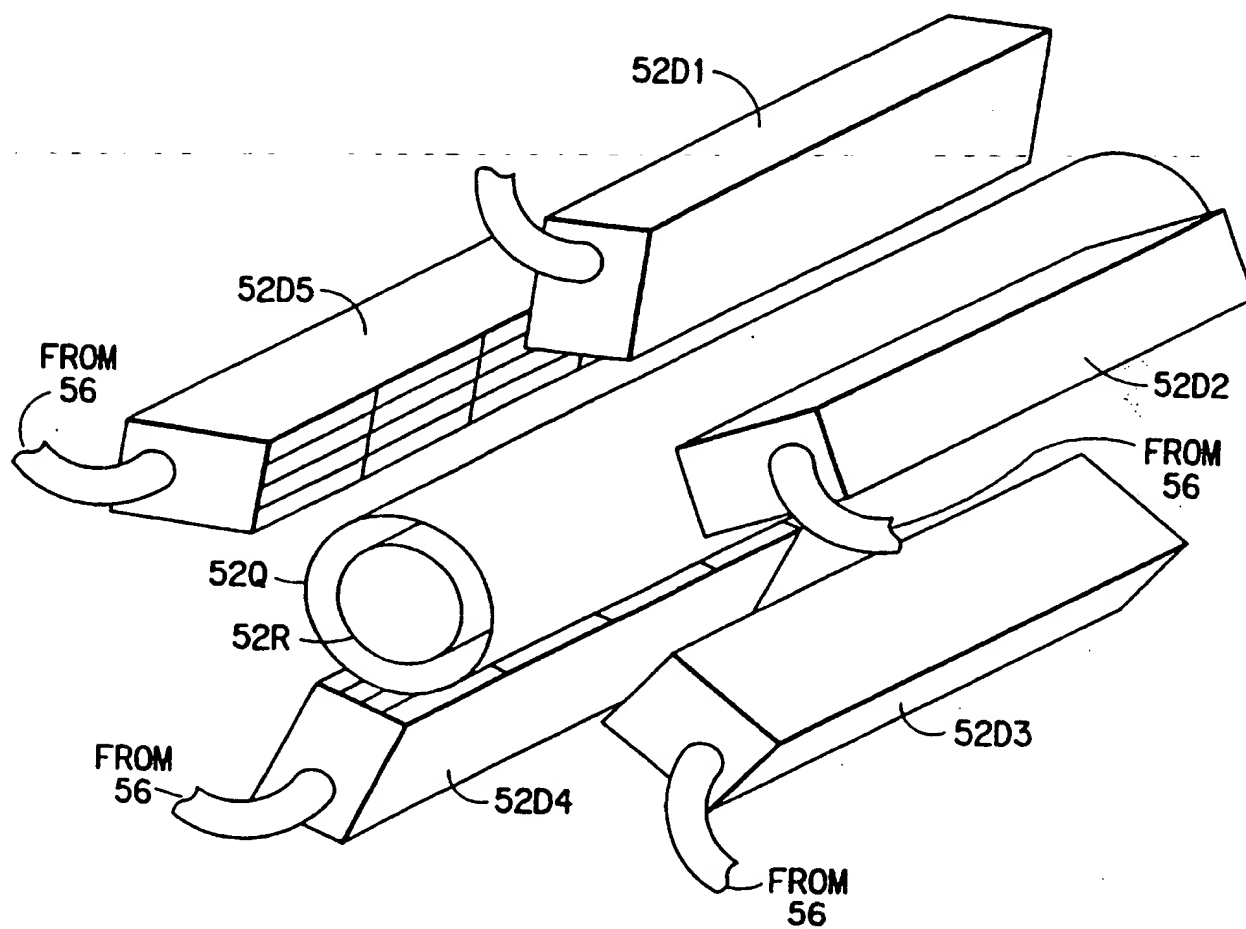


FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 96/17226

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 B23K26/00 B23K26/08 B23K26/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 B23K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US,A,5 168 143 (KOBISA HENRY ET AL) 1 December 1992 cited in the application see column 4, line 26 - column 4, line 30; figure 1 see column 6, line 1 - column 6, line 10 ---	1,2
X	US,A,3 597 578 (SULLIVAN ARTHUR BASIL JOSEPH ET AL) 3 August 1971 see column 4, line 61 - column 4, line 62; figures 1,4 see column 5, line 13 - column 5, line 64 ---	7,11
X	PATENT ABSTRACTS OF JAPAN vol. 007, no. 095 (M-209), 21 April 1983 & JP,A,58 020390 (FUJII JUKOGYO KK), 5 February 1983, see abstract ---	7,18
	-/-	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- * A* document defining the general state of the art which is not considered to be of particular relevance
- * E* earlier document but published on or after the international filing date
- * L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- * O* document referring to an oral disclosure, use, exhibition or other means
- * P* document published prior to the international filing date but later than the priority date claimed

- * T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- * X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- * Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- * &* document member of the same patent family

Date of the actual completion of the international search

23 January 1997

Date of mailing of the international search report

05.02.97

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl,
Fax (+ 31-70) 340-3016

Authorized officer

Concannon, B

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 96/17226

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP,A,0 533 114 (NIPPON ELECTRIC CO) 24 March 1993 see column 4, line 23 - column 4, line 24; figure 3A see column 4, line 56 - column 5, line 6 ---	1,7
A	EP,A,0 458 199 (NTN TOYO BEARING CO LTD) 27 November 1991 ---	1-6,11
X	US,A,5 093 551 (BISHOP DONALD) 3 March 1992 see claims 1-3 ---	14-20
X	EP,A,0 488 402 (EBARA CORP) 3 June 1992 see figure 1 -----	14-20

INTERNATIONAL SEARCH REPORT

information on patent family members

International Application No

PCT/US 96/17226

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-5168143	01-12-92	CA-A- 2034551	30-07-91
		DE-D- 69117996	25-04-96
		DE-T- 69117996	12-09-96
		EP-A- 0440397	07-08-91
		JP-A- 4238683	26-08-92
		SU-A- 1834771	15-08-93

US-A-3597578	03-08-71	BE-A- 712256	16-09-68
		DE-A- 1690637	30-03-72
		FR-A- 1564933	25-04-69
		GB-A- 1215713	16-12-70
		NL-A,B 6803746	17-09-68
		SE-B- 347680	14-08-72
US-A- 3749878	31-07-73		

EP-A-0533114	24-03-93	JP-A- 5075188	26-03-93
		DE-D- 69204131	21-09-95
		DE-T- 69204131	21-03-96
		US-A- 5339328	16-08-94

EP-A-0458199	27-11-91	JP-A- 4028489	31-01-92
		JP-B- 8032369	29-03-96
		JP-A- 4028491	31-01-92
		JP-A- 4061356	27-02-92
		DE-D- 69112272	28-09-95
		DE-T- 69112272	01-02-96
		US-A- 5171963	15-12-92

US-A-5093551	03-03-92	US-A- 5081636	14-01-92
		EP-A- 0507015	07-10-92

EP-A-0488402	03-06-92	DE-D- 69117267	28-03-96
		DE-T- 69117267	02-10-96
		JP-B- 2528760	28-08-96
		JP-A- 5033809	09-02-93
		US-A- 5198637	30-03-93
